2005-09

The effects of quality and timeliness of targeting information on submarine employment of long range anti-ship cruise missiles

Parashak, Paul M.

Monterey California. Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

THE EFFECTS OF QUALITY AND TIMELINESS OF TARGETING INFORMATION ON SUBMARINE EMPLOYMENT OF LONG RANGE ANTI-SHIP CRUISE MISSILES

by

Paul M. Parashak III

September 2005

Thesis Advisor:	Alan Washburn
Second Reader:	Roberto Szechtman

Approved for public release; distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2005	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE**:** The Effects Of Quality And Timeliness Of Targeting Information On Submarine Employment Of Long Range Anti-Ship Cruise Missiles	**5. FUNDING NUMBERS**
6. AUTHOR(S) Paul M. Parashak III	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

Anti-ship cruise missiles (ASCMs) are proliferating throughout the world, with some nations gaining the potential to launch them from submarines. The long range of these missiles implies that the submarine would rely on target detections from other forces. Communication delays and accuracy of locating data influence shot accuracy.

This thesis uses a maneuvering target statistical tracker model (MTST) of target motion and indicates that the submarine can conduct an effective launch with accurate locating information even with long communications delays. The analysis shows that significant degradation of the probability of target intercept occurs for an alerted or evading target.
The analysis then determines how this is affected by the presence of other potential targets for the missile. Two assumptions are made about the performance of the ASCM seeker. A simplistic seeker that selects a target at random performs very poorly if other naval escorts and random neutral shipping are encountered. A more intelligent seeker that uses information about the relative size of the ships and attacks the largest one results in greatly improved performance.

14. SUBJECT TERMS MTST; ASCM; submarine; cruise missile; Kalman filter	**15. NUMBER OF PAGES** 61
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited.

THE EFFECTS OF QUALITY AND TIMELINESS OF TARGETING INFORMATION ON SUBMARINE EMPLOYMENT OF LONG RANGE ANTI-SHIP CRUISE MISSILES

Paul M. Parashak III
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1989

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 2005

Author: Paul M. Parashak III

Approved by: Alan R. Washburn
Thesis Advisor

Roberto Szechtman
Second Reader

James N. Eagle
Chairman, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Anti-ship cruise missiles (ASCMs) are proliferating throughout the world, with some nations gaining the potential to launch them from submarines. The long range of these missiles implies that the submarine would rely on target detections from other forces. Communication delays and accuracy of locating data influence shot accuracy.

This thesis uses a maneuvering target statistical tracker model (MTST) of target motion and indicates that the submarine can conduct an effective launch with accurate locating information even with long communications delays. The analysis shows that significant degradation of the probability of target intercept occurs for an alerted or evading target.

The analysis then determines how this is affected by the presence of other potential targets for the missile. Two assumptions are made about the performance of the ASCM seeker. A simplistic seeker that selects a target at random performs very poorly if other naval escorts and random neutral shipping are encountered. A more intelligent seeker that uses information about the relative size of the ships and attacks the largest one results in greatly improved performance.

THIS PAGE INTENTIONALLY LEFT BLANK

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

Thanks to: First off, I would like to thank Tim Smith, my coworker at COMPACFLT many years ago. You encouraged me to select Operations Research as a graduate degree before I ever knew that I would have the opportunity to attend NPS.

I would like to thank CAPT Jeff Kline, Professor Fitzsimonds, Professor Koerner and the students in the Halsey Group for the outstanding experience tour at Naval War College. The interesting discussions and modeling done there provided the idea for this thesis.

I am deeply indebted to Professor Washburn for his guidance and direction. I am always amazed at your incisive editorial reviews and assistance in getting the model right. Thank you also to Professor Szechtman for the encouragement and interest in this work. My sincerest appreciation goes to CAPT Starr King for your guidance and counsel during my studies at NPS.

Finally, I am truly grateful for the dedication and love of my family. To my Dad and Bonnie, Mom and Bryce, Mary and Shiloh thank you for your support during my entire career and the pride you've expressed in me. And a very special thank you goes to my wife Lalita who is soon to give us our first child. I truly appreciate your patience and kindness every day.

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Many maritime nations are procuring Anti-Ship Cruise Missiles (ASCMs) for use in an anti-access strategy. These missiles can be obtained relatively cheaply from international arms exporting nations. The acquisition of these missiles is intended to prevent the U.S. from bringing its maritime power projection capability within operating range of the coastline.

Sophisticated long-range ASCMs may be useful in an anti-access strategy, if employed effectively. However, the use at long ranges implies that the launching platform will not detect and locate the target itself. This detection is accomplished by other platforms, which then relay the information to the submarine.

This thesis examines the effectiveness of a long-range ASCM attack from a submarine with respect to accuracy and timeliness of targeting information provided. A Java program using a Maneuvering Target Statistical Tracker (MTST) model is used to evaluate the uncertainty in target position for the missile attempting to intercept the target.

Results show that the missile easily intercepts a non-alerted target with reasonable targeting precision at even long communication delays. However, a target that suspects a possible ASCM threat can significantly lower the risk simply by operating at a higher speed. Detecting and evading optimally at launch time further reduces the probability of missile intercept.

The missile attack scenario is extended to investigate the probability of hitting the intended target in the presence of interfering contacts. Two types of missile seeker logic are examined, showing that the performance of ASCMs with simple seeker rules is greatly degraded in the presence of false target choices.

THIS PAGE INTENTIONALLY LEFT BLANK

I. ANTI-SHIP CRUISE MISSILES IN AN ANTI-ACCESS ROLE

> There is a strong temptation to ensure against surprise by assuming the most of enemy capabilities. Certainly past underestimates have sometimes been extremely embarrassing, as in the case of Japan in 1941. However, overestimates may well deter us from actions that are clearly in our interests [Friedman, 2001].

A. ANTI-ACCESS STRATEGY

An important feature of globalization and the rise of regional military powers is the development of an anti-access strategy to counter the U.S. Navy power projection capability [Murdock, 2002]. In a region where the U.S. may not have basing rights or a developed coalition of regional partners, the Carrier Strike Group (CSG) and Expeditionary Strike Group (ESG) would become the focus of conventional power projection capability for the US. They would bring carrier based strike aircraft, Tomahawk cruise missiles and amphibious assault capability to project power against an adversary of the U.S.

Preventing the U.S. from using these mobile bases of power projection is the key feature of an anti-access strategy. The adversary would desire to force the U.S. to remain outside of engagement range of the carrier air wing and cruise missiles and to create an environment that prohibits the landing of amphibious forces from the ESG. The U.S. forces would be required to neutralize the anti-access weapons prior to closing to engagement range or face much higher risks to their naval forces during an engagement.

B. ANTI-SHIP CRUISE MISSILE (ASCM) ROLE AND PROLIFERATION

ASCMs would be useful in an anti-access scenario due to the ability to attack at long range and their relative economy. Although U.S. versions cost upwards of $1Million, many produced by China and Russia can be purchased for less than $400,000 per unit [Bolkcom, 2002].

There is also the perception that these weapon systems do not require the same level of training and sophistication to employ as more conventional naval weapons such as torpedoes or strike aircraft. Most nations that would consider ASCMs as a centerpiece of their anti-access strategy would not have the tactical sophistication to maintain highly trained crews needed to go against the U.S. in a submarine or strike aircraft. So, the simpler method of using missiles is attractive.

The utility of ASCMs to second tier military nations was brought home by the sinking of the HMS Sheffield and the damaging of the USS Stark, both by French made Exocet missiles.

More than a dozen nations have purchased ASCMs for use in access denial scenarios. Many of them have submarine launched variants [Barber, 2001]. The spread of these missiles is difficult to challenge due to the overlap of missile technologies with manned aircraft technologies in the current arms control agreements (the Missile Technology Control Regimes and the Wassenaar Agreement) [Bolkcom, 2002].

Submarine launched ASCMs have a distinct advantage for the attacker in that other platforms are much easier to detect, locate and eliminate before the CSG or ESG comes into range for attack. Land based sites are subject to detection from satellite imaging and surface ships from maritime long-range radar surveillance. However, submarines have the advantage of avoiding these detection tactics.

C. CHALLENGES IN ASCM USE

There are several operational challenges for a nation to overcome to effectively use submarine based ASCMs against the USN. These are often neglected in the analysis of the missiles, as technical, engineering capabilities such as maximum range, radar parameters and warhead type/size are often the focus of the analysis.

D. OVERALL SYSTEM EFFECTIVENESS AGAINST TARGET

There is a danger in ignoring the total system nature of weapon systems. A major focus for many analyses is on terminal capabilities of weapons [Freidman, 2001]. However, this type of analysis ignores the difficulty of detection, localization, classification and identification of the target. Other analyses deal with the ASCM in the presence of the ships integrated defense systems. The mere possession of ASCM systems does not imply that they will be effective in an anti-access mission [Barber, 2001].

Using submarines as launch platforms for ASCMs gives the attacker an advantage. The ESG/CSG has a much more difficult problem detecting and eliminating the launch platform.

However, submarines launching long range ASCMs at near their maximum range will not detect or hold the target on any shipboard sensor. The submarine relies on other ships or aircraft to communicate contact information to it, possibly through a command headquarters. Additionally, submarines are generally operated in a mode that makes communication with them less rapid than with surface vessels. This can be a delay due to communication throughput or due to simply having to alert a submarine to establish communications or wait for a pre-determined communication period. Figure 1 shows that this delay can complicate their use as an ASCM launching platform because the uncertainty in the position of the target expands due to the uncertainty in movement of ships at sea.

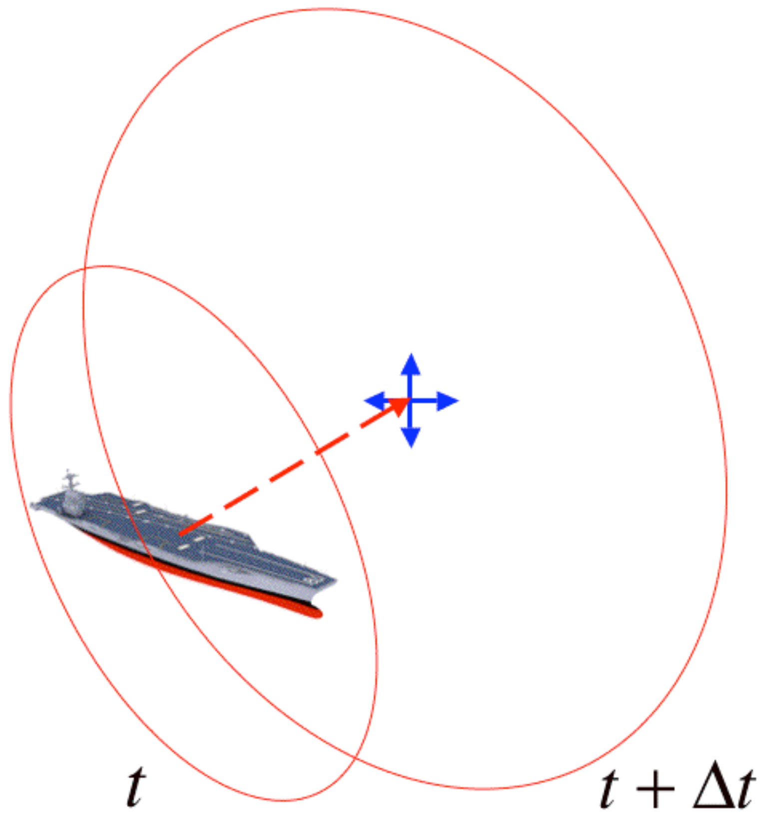

Figure 1. Initial position uncertainty expands after time delay. Depicts a containment curve contour. Orientation of ellipse depends on positional uncertainty, not observed velocity or velocity uncertainty.

E. OVERVIEW OF THESIS

This thesis tries to estimate the degree of competency required of an adversary to use ASCMs effectively to become a credible threat to the U.S. The question of missiles fired at long range, certainly beyond the sensor horizon of the firing platform is examined. The main parameters in question are the locating accuracy required and the timeliness of that data provided to the shooter. Immediate use of grossly inaccurate location data would likely be useless. Alternatively, highly accurate position information provided too late would also be ineffective. Examining the interplay of these two major factors can advise the U.S. as to our vulnerability to the potential threat of ASCMs launched from submarines, and may lead to insights to lessen that vulnerability.

This thesis uses the form of Kalman filter called Maneuvering Target Statistical Tracker (MTST) to estimate the location of the target vessel. One characteristic of the

MTST is that the area of uncertainty in position expands over time and this allows us to accurately estimate the probability of missile intercept. A straight running missile that activates a seeker and sweeps out a volume of probability mass under the MTST bivariate normal approximation is proposed. This bivariate normal is rotated to the reference frame of the missile path and determining the cumulative distribution function of a univariate normal produces an estimated probability of hit. The procedure is run many times with different degrees of accuracy and timeliness of data to develop an insight into the important factors in the parameter space.

Different target postures are assumed in the analysis. The worst-case assumption is for a non-alerted target that is attacked and doesn't detect the attack. This assumption is compared to one where the target moves at higher speeds to make the targeting problem more difficult. Finally, the case where the target is assumed to detect the launch of the missile and is capable of evading optimally is examined to determine how this passive defense tactic can improve its survivability.

THIS PAGE INTENTIONALLY LEFT BLANK

II. METHODOLOGY

A. MANEUVERING TARGET STATISTICAL TRACKER (MTST)

A special type of Kalman filter called Maneuvering Target Statistical Tracker (MTST) is used to estimate the position uncertainty of the target. The general formulation from Washburn is adopted here for the MTST Kalman filter [Washburn 2004]. The state of the target X (x, y position and velocities of the target), is an unknown vector.

$$X = \begin{pmatrix} x \ coordinate \\ y \ coordinate \\ x \ velocity \\ y \ velocity \end{pmatrix}$$

Here $X \sim N(\mu, \Sigma)$, which means that X is distributed as a multivariate normal with mean μ and covariance matrix Σ. Our goal is to obtain the best estimate of the position portion of this Σ matrix (the upper left quadrant of the 4x4 matrix) and use this to determine how well the submarine launched ASCM would do in intercepting the target.

An estimate μ of the state vector is created based on measurements of the target, $Z = HX + V$. In this model the transformation matrix H is a 4x4 identity matrix and $V \sim N(\mu_V, R)$ is the measurement noise. For this model $\mu_V = 0$, which means that the measurements have no systematic biases. The covariance of the measurements of position and velocity of the target is given by:

$$R = \begin{pmatrix} \sigma_{\hat{X}}^2 & \rho_{\widehat{XY}}\sigma_{\hat{X}}\sigma_{\hat{Y}} & 0 & 0 \\ \rho_{\widehat{XY}}\sigma_{\hat{X}}\sigma_{\hat{Y}} & \sigma_{\hat{Y}}^2 & 0 & 0 \\ 0 & 0 & \sigma_{\hat{V}_X}^2 & 0 \\ 0 & 0 & 0 & \sigma_{\hat{V}_Y}^2 \end{pmatrix}$$

In this model for R, the position estimates are allowed to have a non-zero covariance. That means that the ellipse may have an orientation that is not just along the x or y-axis. The velocity errors are assumed to be independent of the position errors, as well as each other.

In other models H may take on different forms. For example, the position and velocity of a target is frequently determined by repetitive observations of just the position, and H then takes on a different form in the MTST implementation.

When a measurement of the target state is made, the Kalman filter gain is first updated:

$$K = \Sigma H^T (H \Sigma H^T + R)^{-1} \qquad (1)$$

Then the state estimate and covariance matrix are updated:

$$\mu^+ = \mu^- + K(Z - \mu_V - H\mu^-) \qquad (2)$$

$$\Sigma^+ = (I - KH)\Sigma^- \qquad (3)$$

The target is assumed to move in accordance with an Ornstein-Uhlenbeck process, which is integrated to give the basis for the motion portion of the MTST model. In the O-U process, mean velocity is zero over the long run, and the movement matrix Φ is given by:

$$\Phi = \begin{pmatrix} 1 & 0 & \delta & 0 \\ 0 & 1 & 0 & \delta \\ 0 & 0 & c & 0 \\ 0 & 0 & 0 & c \end{pmatrix}$$

The parameters of the movement matrix are given by $c = e^{-(\Delta/\tau)}$ and $\delta = \tau(1-c)$, where Δ is the time interval of concern (measurement time and missile intercept time) and τ is the relaxation time for velocity (roughly the time interval between which velocities are assumed independent).

The movement noise is given by the Q matrix adapted from Wagner [Wagner, 1989]:

$$Q = \begin{pmatrix} q_1 & 0 & q_2 & 0 \\ 0 & q_1 & 0 & q_2 \\ q_2 & 0 & q_3 & 0 \\ 0 & q_2 & 0 & q_3 \end{pmatrix}$$

Where $q_1 = \frac{1}{2}s^2\tau[2\Delta - \tau(3-4c-c^2)]$, $q_2 = \frac{1}{2}s^2\tau(1-c)^2$, and $q_3 = \frac{1}{2}s^2(1-c)$. The Q matrix has the effect of inflating the uncertainty of the estimated state of the target by:

$$\Sigma(t+\Delta) = \Phi\Sigma(t)\Phi^T + Q \qquad (4)$$

The state estimate after a time interval is given by:

$$\mu(t+\Delta) = \Phi\mu(t) + \mu_W \qquad (5)$$

Here $\mu_W = 0$, i.e. the target has no overall movement direction.

Here one measurement of target position and velocity is made, and then the estimate degrades over time due to the IOU process. Even if more than one measurement is made on the target prior to the decision to attack with an ASCM, the effect on the model is the same. While the data is being sent from the command center to the attacking submarine, the target state is not being updated and the estimate grows stale, the uncertainty building.

B. ASSUMPTIONS

1. Single Simple Missile

This analysis looks at a single high subsonic sea-skimming missile fired from maximum range of 80 nm. This long range carries with it the assumption that the submarine does not hold the target on any of its sensors.

The missile proceeds down the optimum bearing to sweep out the center of the target AOU. The missile will detect and home on the target with certainty if it is within the missile sweep width.

2. Finite Horizon

The missile type analyzed here is a sea skimming type, most common for ASCMs, and thus has a limited horizon. The lateral range swept out by the missile is derived from the radar horizon and the assumption that the missile radar looks in a 90-degree forward scan +/- 45 degrees. The radar horizon formula gives a good approximation of the assumed sweep width of the missile [after Wagner et. al., 1999].

$$sweep\ width(nm) = 2 * \cos(45^{\circ}) * 1.21 * (\sqrt{missile\ h(ft)} + \sqrt{ship\ h(ft)}\ )$$

Here the missile is proposed to have an altitude of 30 ft. Most ASCMs are employed in a sea-skimming mode, using a radar altimeter at altitudes about ten meters [Bolkcom, 2002b].

3. Submarine Navigation Error

Firing a missile from one moving platform at another moving platform requires knowledge of the location of both the launcher and the target. The submarine's own navigation error can be estimated separately, be assumed to be zero or added onto the targets location error. In this model the submarine comes to shallow depth during communications to receive the targeting information or during launch. During this shallow depth period the submarine can receive navigation updates via Global Positioning System (GPS). Therefore submarine location error is small and is included in the target location error terms.

C. JAVA PROGRAM DESIGN

The Java program ASCM_MTST is organized into five important methods.

- main method
- setParams method
- measurementUpdate method
- movementUpdate method
- integrate method

1. Program main Method

The main method is the portion of the program that starts the program running. An object of the ASCM_MTST class is instantiated and then the data is read into the program.

Data is entered via command line arguments to the ASCM_MTST.class Java Program as in Table 1, below. The program requires all nine to be strings separated by spaces immediately following the program execution command. The program then parses these strings into the numerical values that set the key parameters of the missile-firing model. Without command line arguments, the ASCM_MTST program will prompt for the user to enter the required parameters.

Command line arguments	
s	rms velocity of target (kts)
delta	time delay until launch (min)
tau	relaxation time (min)
sigA	ellipse major axis std dev (nm)
sigRatio	ratio of minor axis: major axis
alpha	angle of ellipse (degrees CCW from X-axis)
sigUxUy	std dev of velocity measurements (kts)
u	observed speed of target (kts)
phi	observed course of target (degrees CCW from X-axis)

Table 1. ASCM_MTST Java program command line arguments (in order)

Following the data input, the main method then invokes the remaining methods of the program to complete the model run.

2. Program setParams Method

The setParams method manipulates all of the input parameters to transform them into values useful to the program. Values that the user inputs as minutes are adjusted into hours. The matrices in the MTST model are instantiated and values populated from the above formulations.

National Institute of Standards and Technology (NIST) JAMA Matrix Package version 1.0.1 is used for matrix manipulation in the Java program [NIST, 2005]. This package was chosen for its accuracy, flexibility and brevity of method calls.

One example of transformation of input data is the population of the R matrix. The user input for the position measurement errors are the ellipse major axis standard deviation (sigA), the "circularity" in percentage or 1 – eccentricity as a percentage (sigRatio) and the rotation angle of the ellipse (alpha). These are more natural to understand than the X, Y component variances and the XY correlation ($\sigma_{\hat{X}}^2, \sigma_{\hat{Y}}^2$, and $\rho_{\widehat{XY}}$).

3. Program measurementUpdate and movementUpdate Methods

The measurementUpdate method takes the input data and changes the original poor guess of the state estimate μ and the covariance matrix Σ based upon equations (1) – (3) above.

The movementUpdate method likewise alters μ and Σ as time and the motion of the target degrade the information obtained from the measurement.

4. Program integrate Method

The spatial uncertainty of the target location at the time of cruise missile intercept is a Cartesian bivariate normal Σ_{POS}, which is found as the upper left sub matrix of Σ. The optimum path of the missile is through the center of this distribution. The orientation of the center is then calculated and the upper quadrant of the MTST covariance matrix is rotated to the frame of reference of the missile to allow simple integration over the width of the missile seeker. If β is the angle of the missile with respect to the x-axis, then:

$$M = \begin{pmatrix} \cos(-\beta) & -\sin(-\beta) \\ \sin(-\beta) & \cos(-\beta) \end{pmatrix}$$

$$\Sigma_{POS} = \begin{pmatrix} \sigma_X^2 & \rho_{XY}\sigma_X\sigma_Y \\ \rho_{XY}\sigma_X\sigma_Y & \sigma_Y^2 \end{pmatrix}$$

$$\Sigma_{Rotated} = M\,\Sigma_{POS}\,M^T$$

This rotation orients the missile flight path along the x-axis and the lower right element in $\Sigma_{Rotated}$ covariance matrix is used as the variance across the missile sweep width. This is integrated about the missile sweep width by a call to a static method in CDF_Normal.class [FPL Statistic Group, 2005.]. This method is based on an accepted algorithm [Hart, 1968] and was validated to four significant digits to a published table [Devore, 2004].

The only output is the calculated probability of missile interception of the target. This output is either displayed via standard screen output via command line or to the text file. The outputs of sequential executions of the program are redirected into a text file for data processing.

D. LIMITATIONS AND WEAKNESSES OF MODEL

1. Motion Model

An Ornstein-Uhlenbeck process provides the model for the motion of the target. This integrates an independent N-S and E-W velocities that vary independently about zero, giving the target motion the nature of a random walk. This model is well suited to ship motion where the assumption holds that the ship will remain in a fixed area over the period of concern.

2. Normal Velocity Errors

The MTST model requires that all measurement errors be normally distributed. This assumption is can be reasonable for position measurement errors. However, there may be problems with velocity measurements.

Visual estimations of ship courses and speeds will likely not result in independent velocity component errors. The speed estimate may be normal, and the course estimate may be normal as well. But, the N-S and E-W components of velocity errors would come from the product of the speed estimate and the sine or cosine of the course estimate. This would not usually yield independent normal errors.

3. Simplistic Engagement

This analysis is for a single missile fired against a single ship. In an anti-access scenario, multiple ships would be operating together in the CSG or ESG. Determining which target, among many is the intended one is the function of missile logic and is not covered in this thesis. This thesis makes an optimistic assumption on the side of the attacker that the missile will perfectly determine its intended target, if it is inside its sweep width. This would logically provide an upper bound on expected missile real world performance.

THIS PAGE INTENTIONALLY LEFT BLANK

III. ANALYSIS

A. NON-ALERTED TARGET

A non-alerted target will normally be moving around its area of operations at moderate speed. The two main factors of location error and time delay are varied across a range of possible values in this design. Time delay of the measurement to missile launch is varied from 10min to 100min in 5min increments. The low end of this is a minimum time from detection to launch, assuming a near immediate response by the command center to authorize missile launch and also a near zero communication delay to provide the data to the submarine. The high end of the scale is to provide a large enough value to determine behavior at an extremely long decision and communication cycle.

For position error, a circular error is assumed from 1 nm to 20 nm standard deviation. Although it is quite possible in the age of Global Positioning System (GPS) navigation systems to obtain positions with accuracy well under 1 nm, this variable also contains the internal submarine navigation error as discussed above as well as any other positional data errors such as datum errors and translation errors across command and control systems. All other parameters are held constant at representative levels as shown below in Table 2.

Non-alerted target parameters

description	program name	value	type
target rms speed	s (kts)	12	held constant
time delay until launch	delta (min)	10-100	varied 19 steps
relaxation time	tau (min)	30	held constant
ellipse std dev	sigA (nm)	1-20	varied 20 steps
"circularity"	sigRatio (%)	100	held constant
ellipse orientation	alpha (degrees)	0	held constant
target speed std dev	sigUxUy (kts)	4	held constant
observed target speed	u (kts)	12	held constant
observed target course	phi (degrees)	45	held constant

Table 2. Inputs for non-alerted target runs.

This provides a grid of 380 distinct missile launch scenarios. These are executed in a batch and collected into an output file. The probability of intercept of the missile against standard deviation and time is displayed as a surface plot in Figure 2. The same data is shown in Figure 3 as a contour plot using the JMP statistical software.

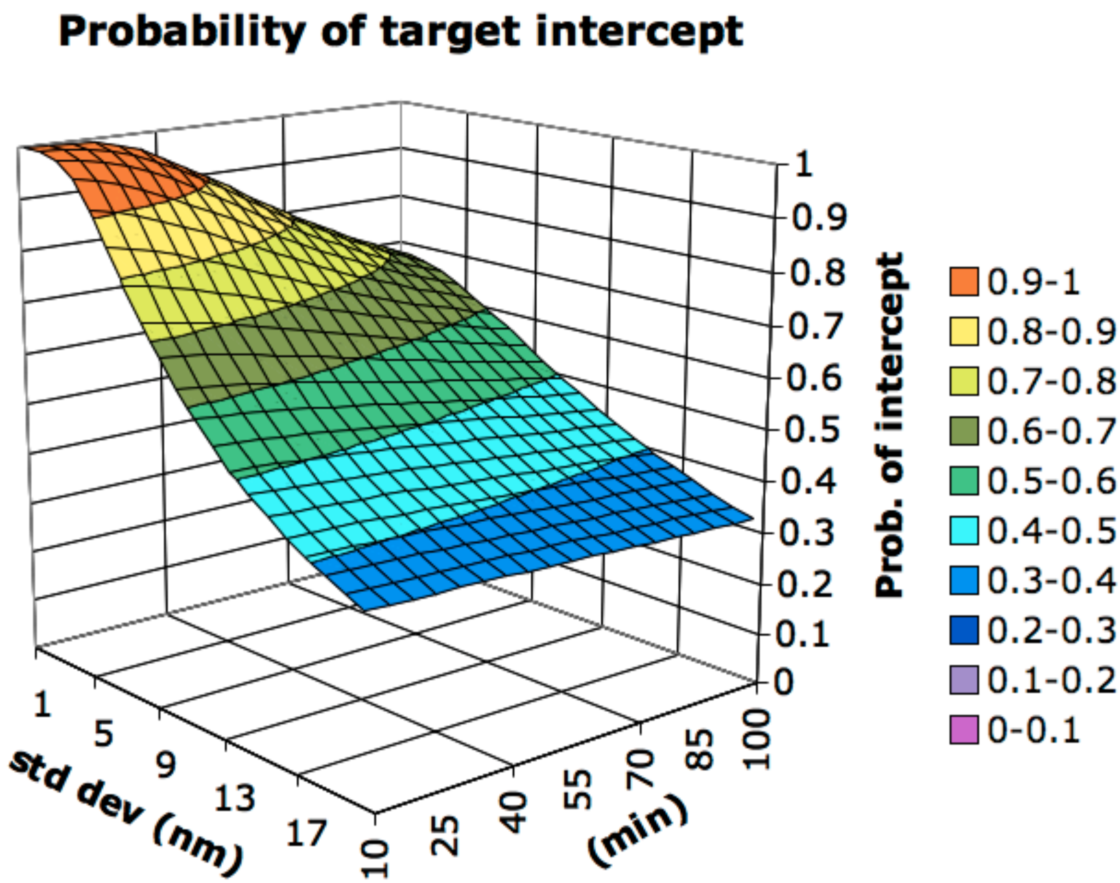

Figure 2. Surface plot of probability of missile intercepting target for 12 knot target rms speed.

For a non-alerted target, we see the probability of missile intercept falls off as either the initial position uncertainty increases or time delay increases. Of the two, accurate location of the target is preferred to having a short time delay. With a 1.0 nm standard deviation of position error, the attacking force can take up to nearly 50 minutes to launch the missile and still have greater than 0.9 probability of the missile intercepting the target.

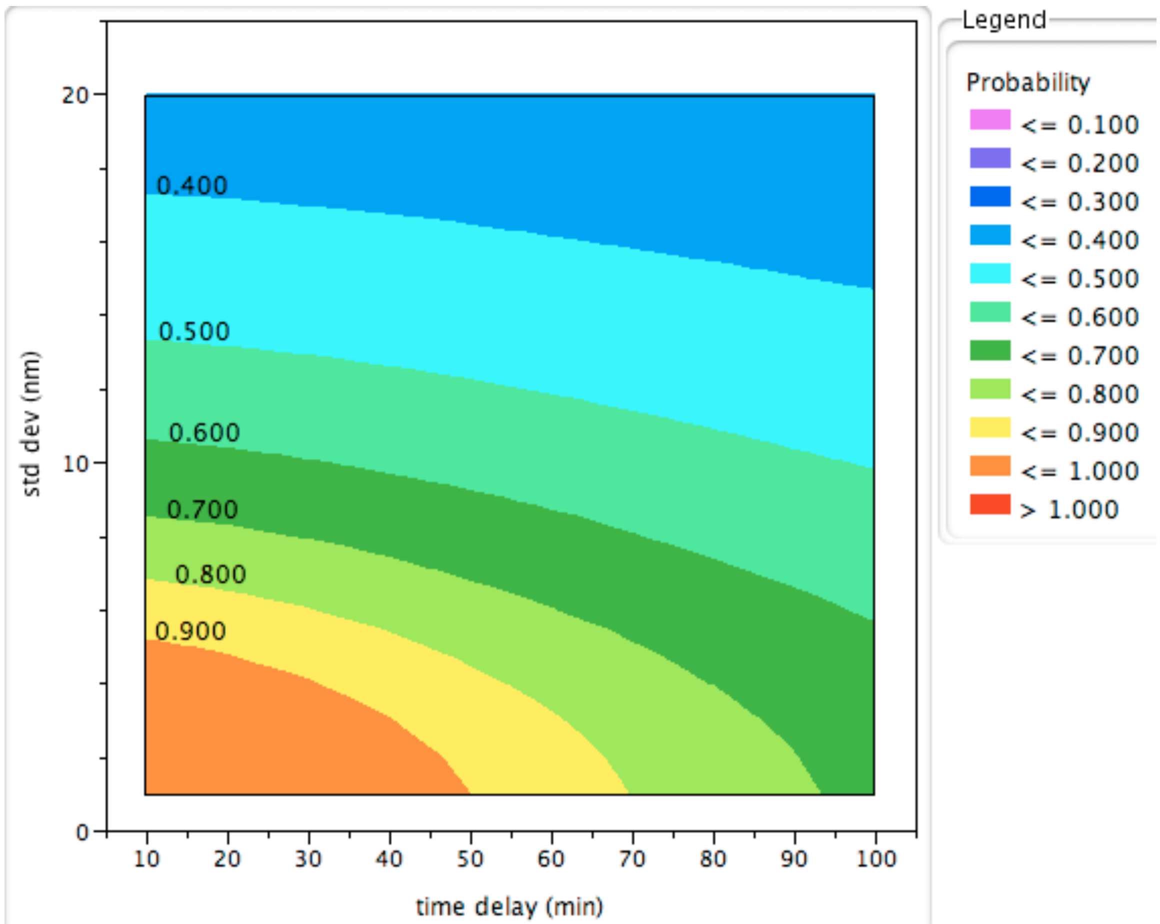

Figure 3. Contour plot of probability of missile intercepting target for 12 knot target rms speed.

B. ALERTED TARGET

A similar experiment was run with the target alerted to possible attack by cruise missiles. The target elects to operate at higher speed to make targeting more difficult for the attacker. The nine command line inputs for the program are provided in Table 3. The only changes from the non-alerted case are the assumed rms speed and the measured target speed, both of which are 25 kts vice 12 kts.

Alerted target parameters			
description	program name	value	type
target rms speed	s (kts)	25	held constant
time delay until launch	delta (min)	10-100	varied 19 steps
relaxation time	tau (min)	30	held constant
ellipse std dev	sigA (nm)	1-20	varied 20 steps
"circularity"	sigRatio (%)	100	held constant
ellipse orientation	alpha (degrees)	0	held constant
target speed std dev	sigUxUy (kts)	4	held constant
observed target speed	u (kts)	25	held constant
observed target course	phi (degrees)	45	held constant

Table 3. Inputs for alerted target runs.

The shape of the surface plot, Figure 4, is roughly the same as with the non-alerted target. However, notice that the probability falls off much more steeply. If the target is aware of possible attack and simply increases speed to 25 kts, the same 1.0 nm position error for the target would result in less than a 0.6 probability of missile intercept after the same 50 min launch delay. To keep the 0.9 probability of intercept, the attacker has to improve the time delay to less than 25 minutes.

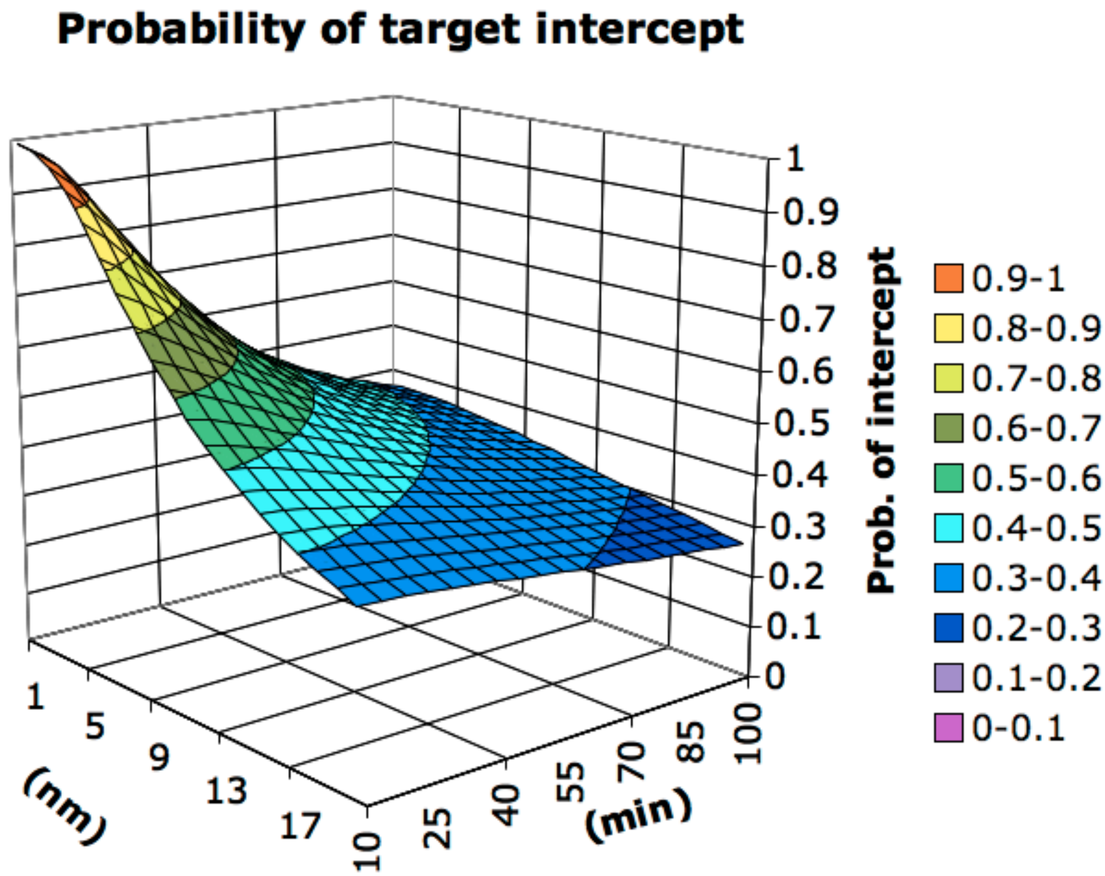

Figure 4. Surface plot of probability of missile intercepting target for 25 knot target rms speed.

The contour plot, Figure 5, shows how much the speed increase has the effect of compressing the x-axis. Previously, the submarine had an extremely good chance of the missile intercepting the target, even at long time delays, as long as the data provided to it was accurate. Here, even with good quality data, the attacker needs to act quickly as their advantage degrades with time.

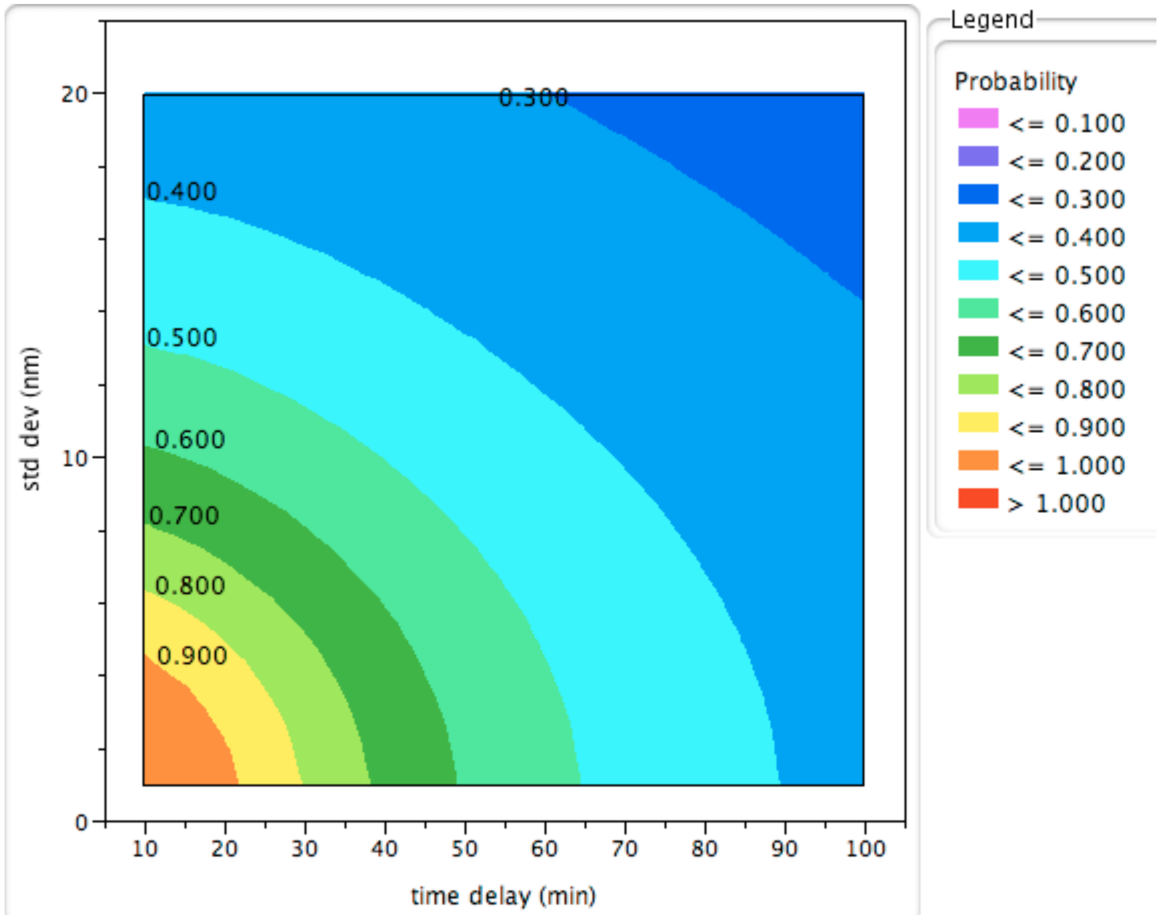

Figure 5. Contour plot of probability of missile intercepting target for 25 knot target rms speed.

C. EVADING TARGET

The CSG or ESG operating in the vicinity of a hostile maritime opponent would likely have aircraft involved in maritime surveillance. These maritime patrol aircraft operating radars may have the ability to provide an early warning to the target to allow it to attempt to evade the ASCM launch. If we give these aircraft the capability to detect the launch of the missile, we can assume that the ship will evade at high speed optimally to maximize the distance moved from its location at the time of the missile launch as shown in Figure 6.

After the missile launch, during the time of evasion, the uncertainty in position due to the delay is paused during the flight time of the missile. This is because when the target detects the missile launch and evades, the random walk nature of the velocity model for MTST are no longer valid.

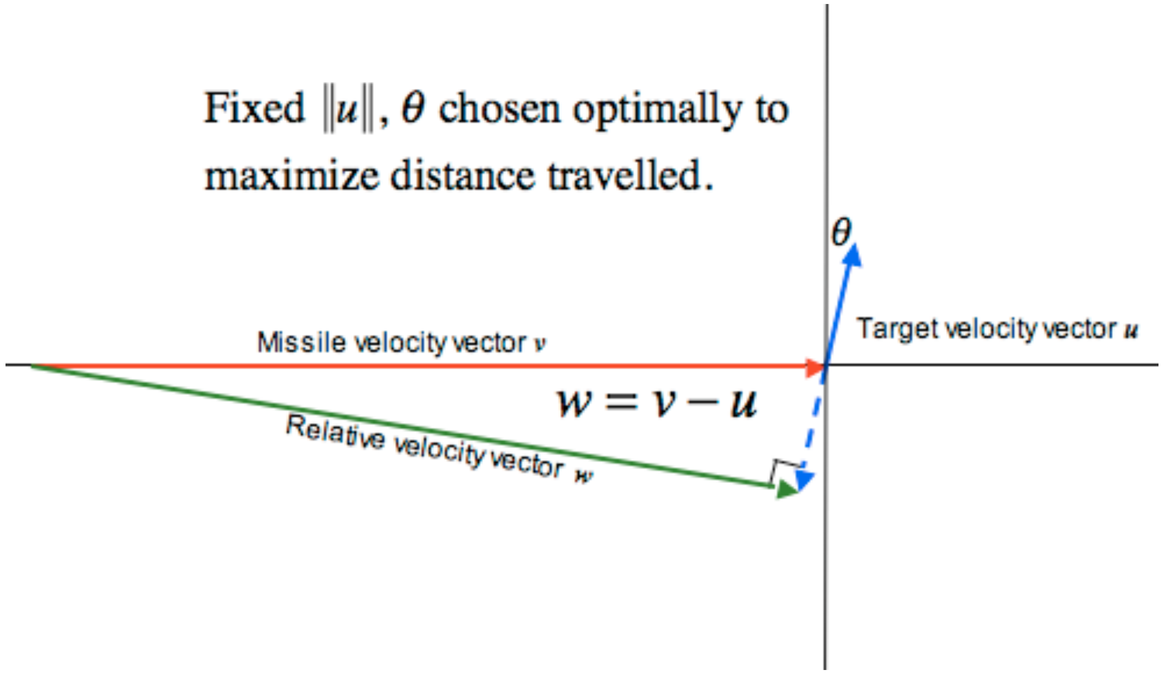

Figure 6. Optimal evasion for target.

For a missile detected at launch at a range of 80 nm, with a speed of 0.85 Mach and a target evasion speed of 35 knots, the target could move 4.98 nm off of the track of the missile.

Results of an alerted target experiment with the missile sweep width offset by the target evasion distance of 4.98 nm are shown in Figure 7.

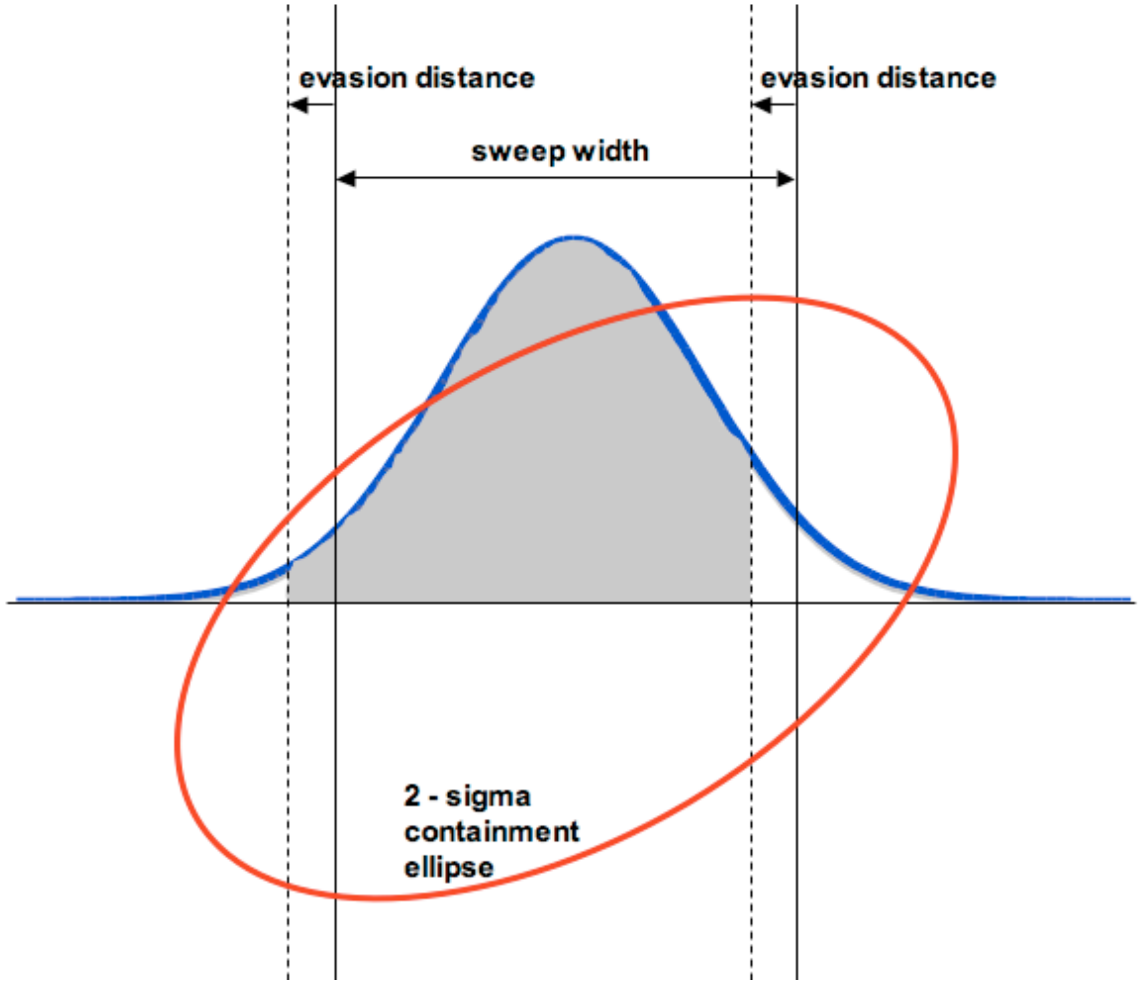

Figure 7. Missile sweep width offset due to target detection of missile launch and optimal evasion.

The results show significant reduction in the probability of intercept for the missile as shown in Figures 8 and 9. This reduction is largest in the regions of highest probability. The example data point of the 1.0 nm position error missile shot could only be delayed by less than 20 minutes to result in the 0.9 probability of intercept.

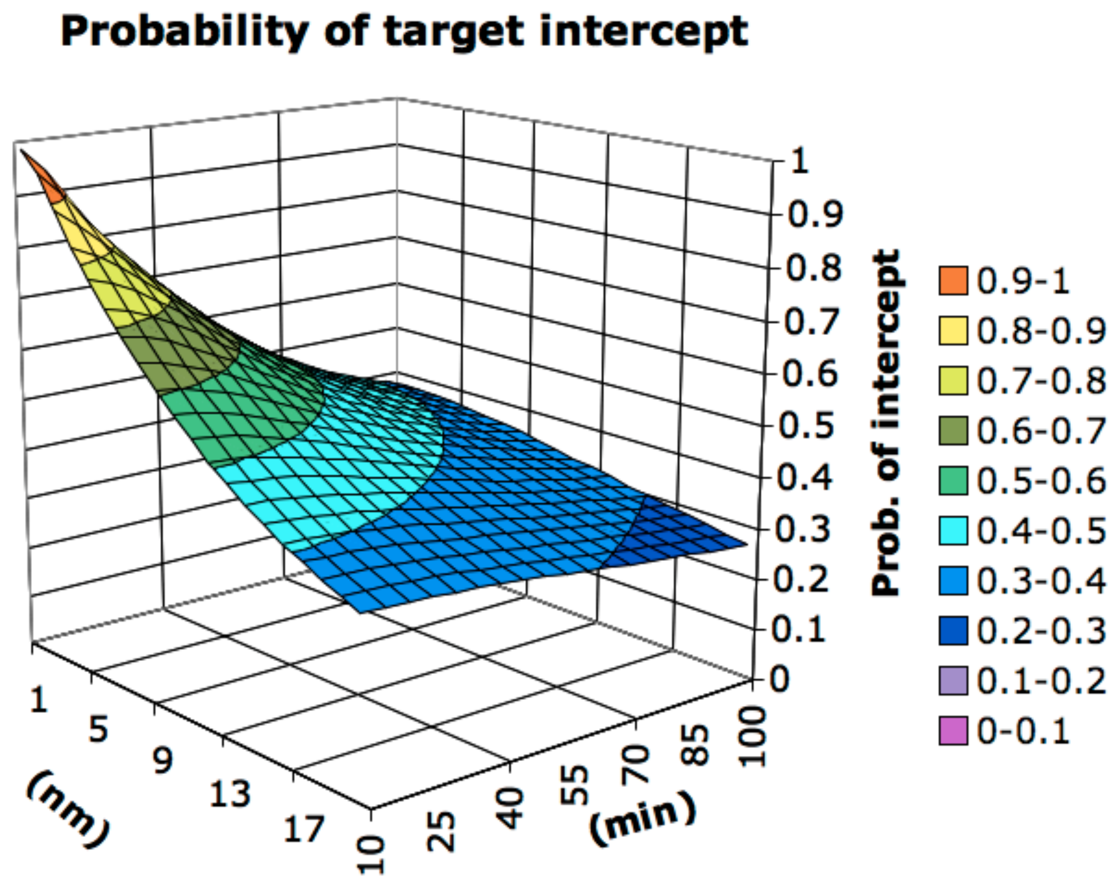

Figure 8. Surface plot of probability of missile intercepting target for 25 knot target rms speed that detects the ASCM at launch and evades at 35 knots.

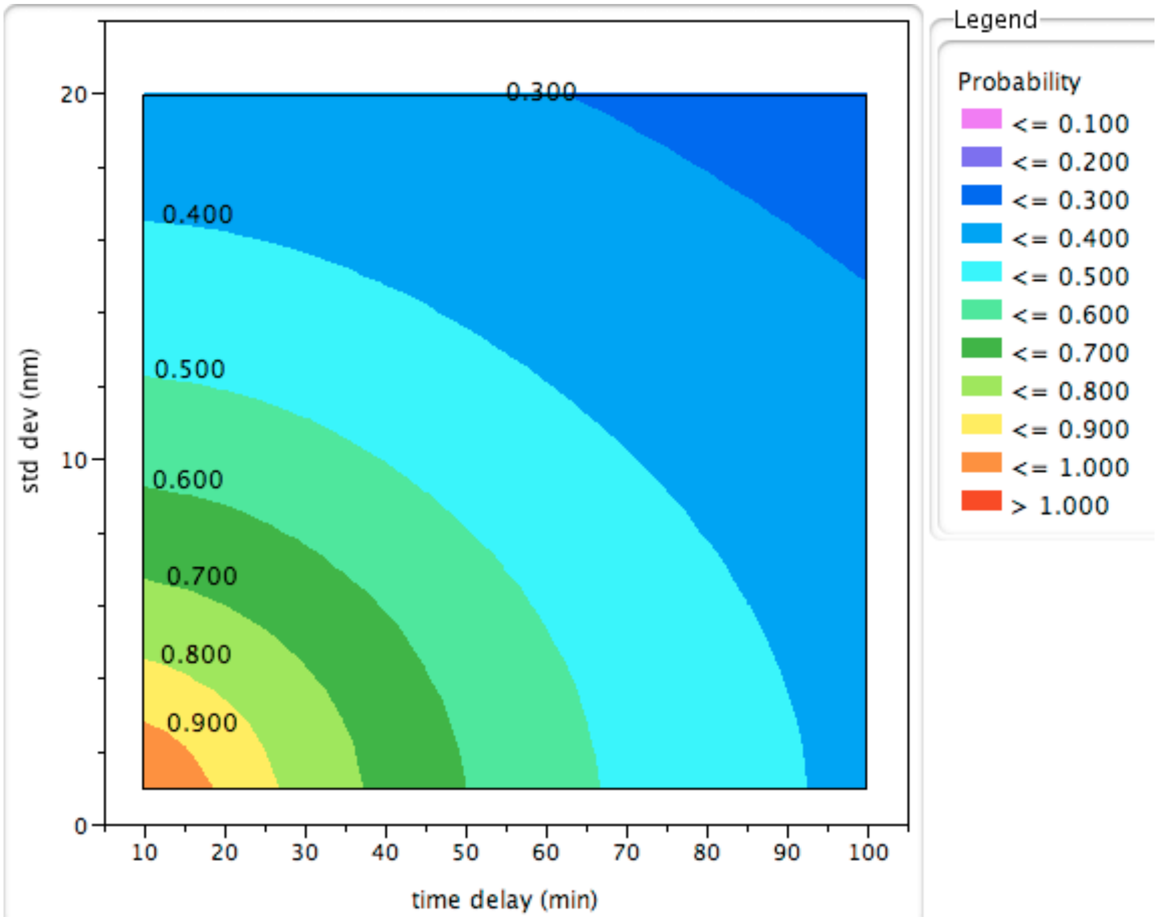

Figure 9. Contour plot of probability of missile intercepting target for 25 knot target rms speed that detects the ASCM at launch and evades at 35 knots.

D. ELLIPSE ECCENTRICITY

The target location error was assumed to be circular in the above experiments, i.e. ellipses with zero eccentricity. The Java program command line argument sigRatio, which is defined as 1 - eccentricity (expressed in %) was fixed at 100 for all of the runs. This eliminated any influences of particular geometries upon the probability density swept out by the missile flight path.

However, some types of measurements such as time difference of arrival/frequency difference of arrival (TDOA/FDOA) or high frequency direction finding (HFDF) provide target location AOUs that can be highly eccentric, due to the geometry of the detection system and target [Stewart, 1997].

Figure 10 shows the results of a 25 knot alerted target fired upon after a 30 minute delay. For the circular location error, the missile has a probability of intercept of 0.54.

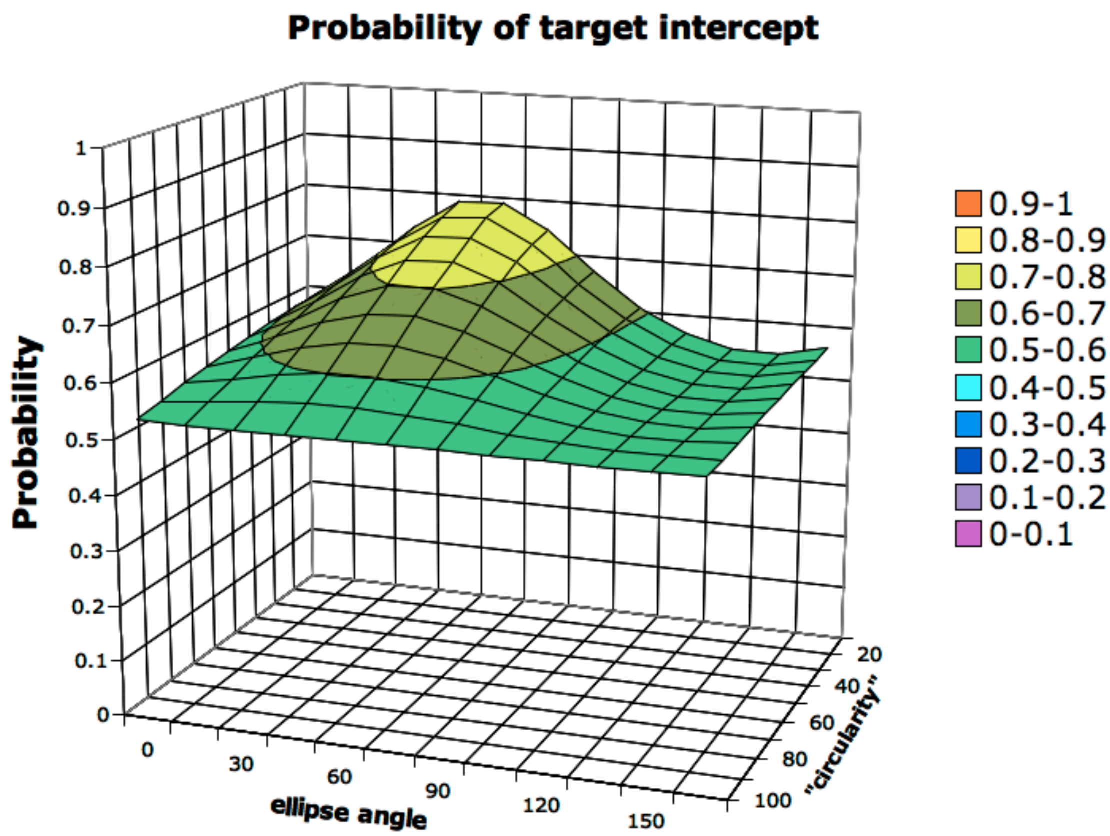

Figure 10. Surface plot of probability of missile intercepting target for 25 knot alerted target after a 30 minute delay. The detection provides an elliptical position error with major axis of 10 nm and different eccentricities.

The enhancement above this baseline occurs when the missile flight path proceeds along the major axis of the target AOU. This effect is more pronounced with ellipses with high eccentricity (low "circularity"). Increases in probability of intercept like this are due to random geometry of the AOU and firing submarine position. Due to a submarine's lack of mobility, it would not be able to reposition to take advantage of this phenomenon. However, an adversary with multiple launch platforms within missile range could use this as a criterion for selecting the platform to attack.

E. FALSE TARGETS AND MISSILE SEEKER TYPES

Previous analysis assumes that the missile will not hit an unintended target. This is either by the target being alone in the ocean or the missile could perfectly discriminate the intended target from non-targets. However, aircraft carriers or large deck amphibious ships do not patrol oceans solitarily.

An extension is to embed the target in a spatial Poisson field of false targets, either neutral shipping or escorts of the target. This would assume that ships are randomly distributed and therefore the missile would encounter a random number of false targets as it sweeps through the target AOU.

An estimate of the key parameter for the Poisson process comes from a shipping density survey [Naval Ocean Systems Command, 1987]. This gives density of merchants, tankers and fishing vessels in the range of 100-300 ships per 10^5 square nm, which gives an approximation of the Poisson parameter, $\lambda_{shipping}$ as 0.002 ships / square nm. In this anti-access scenario, the location of the attack would be closer to shore than this open ocean survey. Therefore, $\lambda_{shipping}$ is doubled to 0.004 ships / square nm.

Added to this must be the fact that the missile would also probably encounter the other ships in the CSG or ESG when searching for the target. Here, we will assume that the number of escorts within the seeker window are distributed Poisson with mean ($\lambda_{escorts}$) of five.

1. Dumb Seeker

A dumb seeker might simply select a target at random, for example the first one that it detects within some spatial window. This would dramatically reduce the probability of hitting the intended target.

Let $p_0 \equiv \text{P(missile intercepts target)}$, which is calculated by MTST_ASCM Java program as before. Then, if N is defined as the number of false targets (neutral shipping and escorts) in the seeker window, then the probability of hit is:

$$p_{hit} = p_0 E\left[\frac{1}{\mathrm{N}+1}\right]$$

The model used in MTST_ASCM assumes a 30 ft missile altitude and the ability to see ships that are greater than 25 ft in height. This results in a missile sweep width of almost 18 nm. Using this and a downrange distance of 40 nm with the missile radar on, gives a Poisson rate for neutral shipping $\lambda_{shipping} * Area_{\text{seeker}} = 2.88$, and an overall rate of 7.88. $E\left[\frac{1}{\text{N}+1}\right]$ is then obtained by numerical computation of $\sum_{j=0}^{\infty}\frac{\lambda^j}{j!}e^{-\lambda}\left(\frac{1}{j+1}\right)$, which is approximately 0.127. Figure 11 shows a surface plot of the resulting p_{hit} for a dumb missile shot at an alerted target.

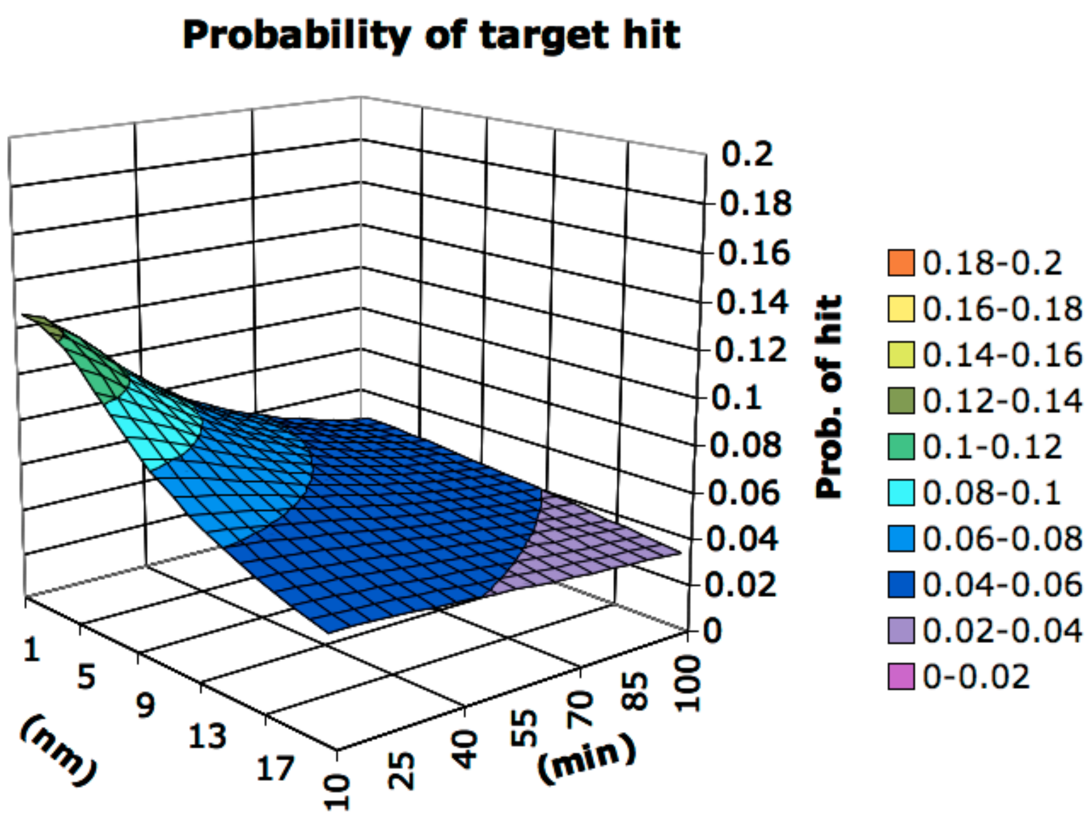

Figure 11. Surface plot of probability of hit p_{hit} for a missile with a dumb seeker attacking a 25 knot alerted target. Note the change in scale of the z-axis from the previous figures.

This type of missile seeker results in an extremely poor hit probability of the intended target. However, evaluating $E\left[\frac{N_{escorts}}{N_{total}+1}\right]$ in a spreadsheet shows that nearly 56% of the time, the missile is homing on other CSG escorts and not the carrier, even when the carrier is in the seeker window. While this is not the intended result, the attacking force would still be successful in attacking the CSG. This may be a satisfying result for an attacking force aimed at anti-access goals.

2. Smarter Seeker

With the rapid increase of high-speed portable computing power, a missile could take advantage of radar return information. From the range and strength of the radar return, a rough measure of radar cross section (RCS) of the contact can be inferred. A smarter missile seeker then selects the contact with the highest observed radar cross section.

Radar cross section is very dependent on the aspect angle of the target, among other factors [Wagner et. al., 1999]. We assume that RCS on dB scale is uniformly distributed from a maximum value to a minimum value, and aspect angle is random for the target and any other ships (including escorts). Figure 12 illustrates some values for the following example. The target (carrier) generally has a larger RCS than other ships, but there are some random orientations that would show a broadside aspect for an escort and a narrow one for the target.

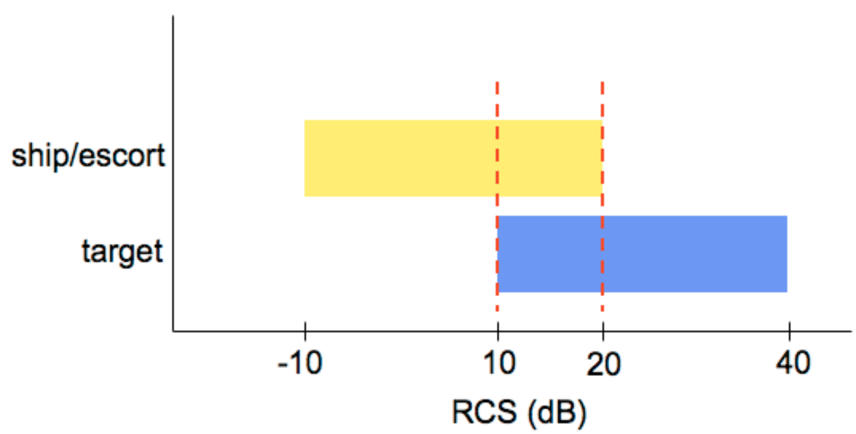

Figure 12. Radar Cross Section (RCS) example values for smarter seeker model.

When this overlap is present with $X \equiv$ RCS of target (carrier) $\sim \mathrm{U}(X_{\min}, X_{\max})$ and $Y_i \equiv$ RCS of shipping/escort $i \overset{\text{iid}}{\sim} \mathrm{U}(Y_{\min}, Y_{\max})$, then the probability of this seeker hitting the target in the presence of n other ships is:

$$\mathrm{P(target\ hit)} = \mathrm{P}(X > Y_1 \cap X > Y_2 \cap \cdots \cap X > Y_\mathrm{n})$$

$$= \int_{X_{\min}}^{X_{\max}} \left[\mathrm{P}(X > Y_i\right]^{\mathrm{n}} f(x)dx$$

$$= \int_{X_{\min}}^{Y_{\max}} \left[\frac{x - Y_{\min}}{Y_{\max} - Y_{\min}}\right]^{\mathrm{n}} \left(\frac{1}{X_{\max} - X_{\min}}\right) dx + \int_{Y_{\max}}^{X_{\max}} \left(\frac{1}{X_{\max} - X_{\min}}\right) dx$$

$$= \left(\frac{1}{\mathrm{n}+1}\right)\left(\frac{Y_{\max} - Y_{\min}}{X_{\max} - X_{\min}}\right)\left[1 - \left(\frac{X_{\min} - Y_{\min}}{Y_{\max} - Y_{\min}}\right)^{\mathrm{n}+1}\right] + \left(\frac{X_{\max} - Y_{\max}}{X_{\max} - X_{\min}}\right)$$

The missile seeker would only be successful if the observed RCS of the target were greater than all of the others encountered by the missile. The values in this example show that the carrier would have only a 94.4% chance of having an observed RCS greater than a single smaller ship. But in the presence of a Poisson field of neutral shipping and escorts with mean 7.88, the probability of missile hitting the carrier given that it intercepts the carrier is reduced down to 0.776. Figure 13 shows the results of using this model of the seeker behavior.

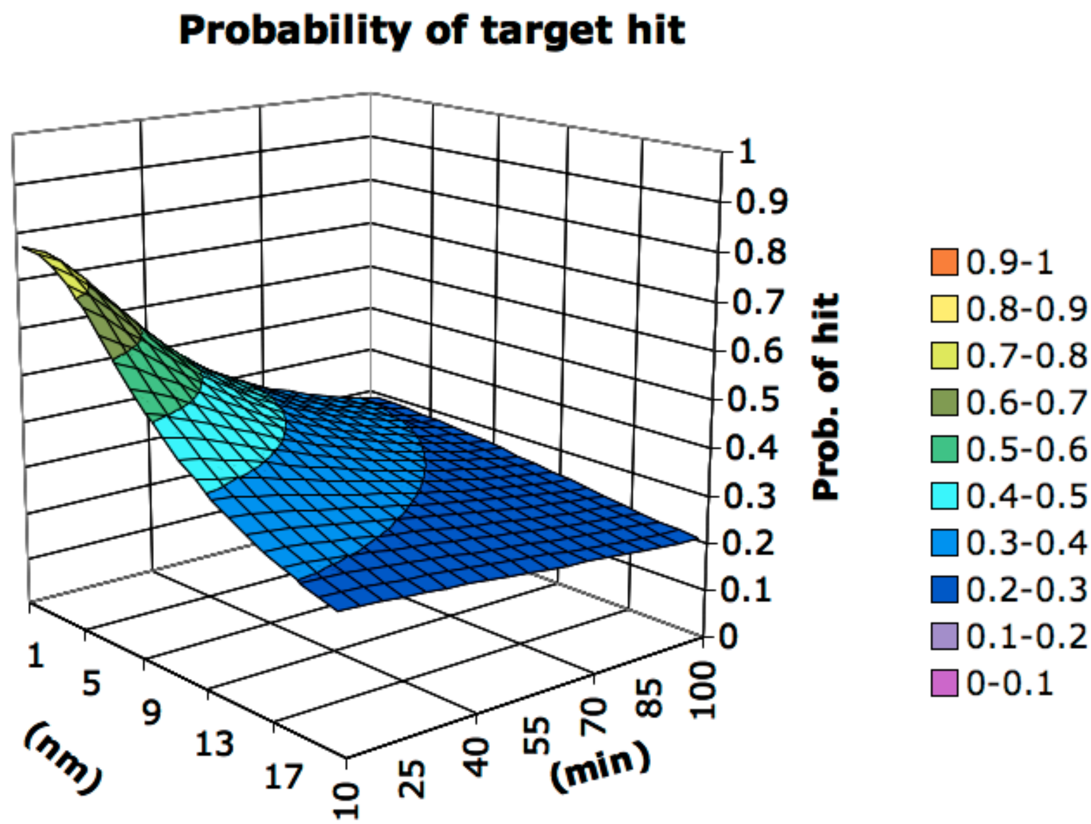

Figure 13. Surface plot of probability of hit for a missile with a smarter seeker attacking a 25 knot alerted target.

This is a reasonable result, as it is not reduced so much that the probability of hit is not worth the effort to attack. However, this does show that to take advantage of the region of probability greater than 0.5, the attacker needs high quality data in a timely matter.

IV. SUMMARY AND RECOMMENDATIONS

A. SUMMARY

A maneuvering target statistical tracker Kalman filter based tracking model is used to determine location uncertainty of a moving target in a naval anti-access scenario. The attacking nation detects the target, a carrier or large deck amphibious ship and relays this information to a submarine. There is a delay in this communication. The MTST model inflates the original position uncertainty during this delay due to the unknown and unobserved motion of the target. The submarine then launches an ASCM to optimally attack the target.

A Java based program is used to facilitate repetitive analysis of different launch configuration. The analysis focuses on the degree of precision of locating information and the timeliness of the ASCM launch.

A surprise attack of a non-alerted target at moderate speed would have a high probability of successful missile interception of the target. In an anti-access conflict scenario, in which the U.S. would likely have suspicion of a potential ASCM attack, the use of speed alone degrades the attacker's chances of success greatly. In a highly alert, defensive posture, a minimal evasion (~ 5nm) during missile flight would also reduce the probability of success for the missile firing.

Two types of missile seekers are modeled. A simplistic seeker is one that selects a target to attack at random from among those it encounters. This results in a highly inept missile in any but the sparsest populated oceans.

The second seeker type is one that is designed to attack the largest potential target presented to it. Even with this more sophisticated seeker, a significant reduction in performance is seen in the presence of even a moderate false target population.

The defender, in the presence of a potential long range ASCM threat may take advantage of mobility, evasion and interfering shipping to confound the missile success probability.

B. POSSIBLE EXTENSIONS AND FUTURE RESEARCH TOPICS

1. More Complex Seeker Pattern

The missile assumed in this thesis is one that makes one sweep down the optimum bearing to the target. There are other ways for a missile seeker to sweep out a target area. Most of these are used to avoid homing on false targets. These more complex patterns may be analyzed by simulation with an MTST model for targeting.

2. Incorporation of Synchronized Missile Salvo

This analysis is an estimation of the potential of a limited attack. Multiple launches from a single submarine may be used to improve the coverage and to increase the complexity of defending the target for the CSG escorts.

3. Incorporation of Target Defenses

When interfering shipping is brought into the model, the presence of CSG escorts is assumed. A primary mission of this screen is Anti-Air Warfare, specifically missile defense. Adding the capability for the screen to defend the carrier would improve the prospects for the U.S. This type of analysis could be done by simulation, because many of the outcomes would be dependent on the situational geometry.

APPENDIX: ASCM_MTST JAVA CODE

```
import Jama.Matrix;

/*
 * File: ASCM_MTST.java
 * Created: Apr 20, 2005, 12:29:12 PM
 */

/**
 * <P>
 * Maneuvering Target Statistical Tracker class for determining Anti-Ship
 * Cruise Missile performance using data obtained from non-organic sensors.
 * Requires user input for parameters in the form of command line arguments
 * of length nine.
 * </P>
 *
 * @author Paul Parashak
 */
public class ASCM_MTST {
    //class constants

    // initial values for sigma matrix
    public static final double POS_SIGMA = 100.0;
    public static final double SPEED_SIGMA = 12.0;
    public static final double MISSILE_ALT = 30.0;
    public static final double TARGET_HOE = 25.0; // effective height of target
    public static final double MISSILE_SPEED = 562.3; // .85*speed of sound @sl
    public static final double SUB_X = 80.0;
    public static final double SUB_Y = 0.0;

    //class variables

    //instance variables

    // half width of missile look for integration
    protected double width;
    protected double delta;
    private double littleDel;
    // relaxation time
    protected double tau;
    private double c;
    protected double s;
    private double qOne;
    private double qTwo;
    private double qThree;
    private double sigX;
    private double sigY;
    protected double sigUxUy;
    protected double sigA;
    private double sigB;
    protected double alpha;
    private double rho;
    // PHI matrix
    private Matrix phiMatrix;
    // H matrix
    private Matrix hMatrix;
    // Q matrix
    private Matrix qMatrix;
    // R matrix
    private Matrix rMatrix;
    // Mean of movement matrix noise
```

```
private Matrix muW;
// Mean of measurement matrix noise
private Matrix muV;
// Mean target state
protected Matrix mu;
// Covariance of ship state
protected Matrix sigmaMatrix;
// Measurement
private Matrix z;
// Kalman gain matrix
private Matrix kalmanGain;
// rotation matrix for input and output
protected Matrix rotation;
private Matrix inputCov;
protected double u;
protected double phi;
protected double sigRatio;

// class methods

/**
 * Print method to shorten the "System.out.println" statements
 * in the code body. Enhances readability of code.
 *
 * @param in
 * String that will be printed on next line.
 */
public static void print(String in) {
    System.out.println(in);
}

//constructor methods

/**
 * Constructor method for class.
 */
public ASCM_MTST() {
}

//instance methods

/**
 * Sets all the parameters of the Kalman filter parameters and
 * matrices for further calculations.
 */
public void setParams() {
    delta /= 60.0;
    delta += SUB_X/MISSILE_SPEED;
    tau /= 60.0;
    c = Math.exp(-(delta / tau));
    littleDel = tau * (1 - c);
    q = s * s * (1 - c * c);

    qOne = 0.5 * s * s * tau * (2 * delta - tau * (3 - 4 * c + c * c));
    qTwo = 0.5 * Math.pow( (s * Math.sqrt(tau) * (1 - c )), 2);
    qThree = 0.5 * s * s * (1 - c);

    //set measurment of position and velocity of target
    z = new Matrix(4, 1);
    z.set(2,0,u*Math.cos(Math.toRadians(phi)));
    z.set(3,0,u*Math.sin(Math.toRadians(phi)));

    width = Math.cos(Math.toRadians(45.0)) * 1.21 * (Math.sqrt(MISSILE_ALT)
                + Math.sqrt(TARGET_HOE));
    muV = new Matrix(4, 1);
```

```
    muW = new Matrix(4, 1);

    mu = new Matrix(4, 1, 100.0);

    //set rho, sigX, sigY
    alpha = Math.IEEEremainder(alpha, 360);

    alpha = Math.toRadians(alpha);

    inputCov = Matrix.identity(2, 2);
    inputCov.set(0, 0, sigA * sigA);
    sigB = sigRatio*sigA/100;
    inputCov.set(1, 1, sigB * sigB);

    rotation = Matrix.identity(2, 2);
    rotation.set(0, 0, Math.cos(alpha));
    rotation.set(0, 1, -Math.sin(alpha));
    rotation.set(1, 0, Math.sin(alpha));
    rotation.set(1, 1, Math.cos(alpha));

    Matrix rotCov = rotation.times(inputCov.times(rotation.transpose()));

    sigX = Math.sqrt(rotCov.get(0, 0));
    sigY = Math.sqrt(rotCov.get(1, 1));
    rho = rotCov.get(0, 1) / (sigX * sigY);

    sigmaMatrix = Matrix.identity(4, 4);
    sigmaMatrix.set(0, 0, POS_SIGMA * POS_SIGMA);
    sigmaMatrix.set(1, 1, POS_SIGMA * POS_SIGMA);
    sigmaMatrix.set(2, 2, SPEED_SIGMA * SPEED_SIGMA);
    sigmaMatrix.set(3, 3, SPEED_SIGMA * SPEED_SIGMA);

    hMatrix = Matrix.identity(4, 4);

    rMatrix = Matrix.identity(4, 4);
    rMatrix.set(0, 0, sigX * sigX);
    rMatrix.set(0, 1, rho * sigX * sigY);
    rMatrix.set(1, 1, sigY * sigY);
    rMatrix.set(1, 0, rho * sigX * sigY);
    rMatrix.set(2, 2, sigUxUy * sigUxUy);
    rMatrix.set(3, 3, sigUxUy * sigUxUy);

    phiMatrix = Matrix.identity(4, 4);
    phiMatrix.set(2, 2, c);
    phiMatrix.set(3, 3, c);
    phiMatrix.set(0, 2, littleDel);
    phiMatrix.set(1, 3, littleDel);

    qMatrix = new Matrix(4, 4);
    qMatrix.set(0, 0, qOne);
    qMatrix.set(1, 1, qOne);
    qMatrix.set(0, 2, qTwo);
    qMatrix.set(1, 3, qTwo);
    qMatrix.set(2, 0, qTwo);
    qMatrix.set(3, 1, qTwo);
    qMatrix.set(2, 2, qThree);
    qMatrix.set(3, 3, qThree);
}

/**
 * Updates the state estimate and covariance matrices for the initial
 * measurement matrix.
 */
public void measurmentUpdate() {
```

```
    kalmanGain = sigmaMatrix.times(hMatrix.transpose()).times(
            ((hMatrix.times(sigmaMatrix.times(hMatrix.transpose())))
                    .plus(rMatrix)).inverse());
    mu.plusEquals(kalmanGain.times(z.minus(muV.minus(hMatrix.times(mu)))));
    sigmaMatrix = Matrix.identity(4, 4).minus(kalmanGain.times(hMatrix))
            .times(sigmaMatrix);
}

/**
 * Updates the state estimate for the delay in missile launch and travel
 * time of the missile to the target.
 */
public void movementUpdate() {
    mu = phiMatrix.times(mu).plus(muW);

    sigmaMatrix = phiMatrix.times(sigmaMatrix.times(phiMatrix.transpose()))
            .plus(qMatrix);

}

/**
 * Calculates the probability that the missile will hit the target.
 * Initially, the path of the missile through the probability ellipse is
 * determined and then the upper quadrant (position uncertainty) of the
 * sigma matrix is put through a rotation transformation. Then a lookup is
 * done in a
 */
public void integrate() {
    double theta = -Math.atan((mu.get(1, 0) - SUB_Y)
            / (mu.get(0, 0) - SUB_X));

    Matrix posCov = sigmaMatrix.getMatrix(0, 1, 0, 1);
    rotation.set(0, 0, Math.cos(theta));
    rotation.set(0, 1, -Math.sin(theta));
    rotation.set(1, 0, Math.sin(theta));
    rotation.set(1, 1, Math.cos(theta));
    Matrix ellipse = rotation.times(posCov.times(rotation.transpose()));

    double sigma = Math.sqrt(ellipse.get(1, 1));

    print(Double.toString(1.0 - 2.0 * CDF_Normal.normp(-width / sigma)));

}

//main method
public static void main(String[] args) {
    ASCM_MTST runIt = new ASCM_MTST();
    if (args.length == 9) {
        try {
            runIt.s = Double.parseDouble(args[0]);
            runIt.delta = Double.parseDouble(args[1]);
            runIt.tau = Double.parseDouble(args[2]);
            runIt.sigA = Double.parseDouble(args[3]);
            runIt.sigRatio = Double.parseDouble(args[4]);
            runIt.alpha = Double.parseDouble(args[5]);
            runIt.sigUxUy = Double.parseDouble(args[6]);
            runIt.u = Double.parseDouble(args[7]);
            runIt.phi = Double.parseDouble(args[8]);
        }
        catch (NumberFormatException e) {
            System.err
            .println("There was an error in at least one of your inputs."
            + "\nYou need to input nine doubles separated by spaces."
            + "\nIn order these should be:"
            + "\n  s - target rms speed (kts)"
```

```
                 + "\n  delta - time delay until launch (min)"
                 + "\n  tau - relaxation time (min)"
                 + "\n  sigA - position error ellipse major axis std dev (nm)"
                 + "\n  sigRatio - ratio of major axis : minor axis (%)"
                 + "\n  alpha - angle of ellipse (degrees CCW from X-axis)"
                 + "\n  sigUxUy - std dev of velocity measurements (kts)"
                 + "\n  u - observed speed of target (kts)"
                 + "\n  phi - observed course of target (degrees CCW from X-
axis)"
                 + "\n\nPlease correct arguments and run again.");
            }
        }

        else {
            System.err.println("Must have nine arguments for for automatic
input.");
        }
        runIt.setParams();
        runIt.measurmentUpdate();
        runIt.movementUpdate();
        runIt.integrate();
    }
}
```

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Barber, Arthur H. III and Delwin L. Gilmore, "Maritime Access: Do Defenders Hold All the Cards?" *Defense Horizons.* National Defense University, October 2001.

Bolkcom, Christopher and Sharon Squassoni, "Cruise Missile Proliferation," *Congressional Research Service Report for Congress*, July 3, 2002.

Bolkcom, Christopher, "Cruise Missile and UAV Threats to the United States," Hearing Before the International Security, Proliferation and Federal Services Subcommittee, June 11, 2002.

Devore, Jay L., *Probability and Statistics*, 6th Edition, Brooks/Cole, 2004.

FPL Statistic Group, "Probability Distributions Java Package," USDA Forest Service, accessed July 2005 at www1.fpl.fs.fed.us/distributions.html

Friedman, Norman, "Globalization of Antiaccess Strategies," *Globalization and Maritime Power*, National Defense University, 2002.

Hart, J.F. and others, *Computer Approximations*, Wiley, 1968.

JAMA, "JAMA: A Java Matrix Package," National Institute of Standards and Technology, accessed June 2005 at math.nist.gov/javanumerics/jama.

Mann, Joelle J., "ASW Fusion on a PC," *Naval Postgraduate School Thesis*, June 2004.

Murdock, Clark A., "The Navy in an Antiaccess World," *Globalization and Maritime Power*, National Defense University, 2002.

Naval Ocean Systems Center (NOSC), *Shipping Density Atlas of the World*, NOSC Technical Report 1165, April 1987.

Stewart, Andrew D., "Comparing Time-Based and Hybrid Time-Based/Frequency Based Multi-Platform Geo-Location Systems," *Naval Postgraduate School Thesis*, September 1997.

Wagner, Daniel H., “Naval Tactical Decision Aids”, *Naval Postgraduate School Lecture Notes*, September 1989.

Wagner, Daniel H., W. Charles Mylander and Thomas J. Sanders, *Naval Operations Analysis*, 3rd Edition, Annapolis: Naval Institute Press, 1999.

Washburn, Alan, *A Short Introduction to Kalman Filters*, Naval Postgraduate School, 2004.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Professor Washburn
   Naval Postgraduate School
   Monterey, California

4. Professor Szechtman
   Naval Postgraduate School
   Monterey, California

5. CAPT Kline
   Naval Postgraduate School
   Monterey, California

6. Professor Fitzsimonds
   Naval War College
   Newport, Rhode Island

7. Professor Koerner
   Naval War College
   Newport, Rhode Island